SPHERE
(Spectro-Polarimetric High-contrast Exoplanet REsearch)
A Planet Finder Instrument for the VLT

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Science objectives

- High contrast imaging down to planetary masses
- Investigate large target sample: statistics, variety of stellar classes, evolutionary trends
- Complete the accessible period window
- First order characterization of the atmosphere (clouds, dust content, Methane, water absorption, effective temperature, radius, dust polarization)

Understand the planetary system origins
Science objectives

- Radial Velocity
- Large Surveys
- HC & HAR Imaging
- Transits
- Stars
- BDs
- Planets
- μ Lensing
SPHERE
High level requirements

- **Scientific requirements**
  - Gain up to 2 orders of magnitude in contrast as compared to current instrumentation
  - Reach short separations: 0.1" - 3" (1-100AU)
  - Survey a large number of targets

- **High contrast detection capability**
  - Extreme AO (turbulence correction)
    - feed coronagraph with well corrected WF
    - SR ~ 90% in H-band
  - Coronagraphy (removal of diffraction pattern)
    - high dynamics at short separations
  - Differential detection (removal of residual defects)
    - calibration of non common path aberrations
    - pupil and field stability
    - smart post processing tools

- **High sensitivity**
  - optimal correction up to V ~ 9-10
**Concept overview**

**Common Path**
- Fore optics
- Extreme AO
- NIR Coronagraph

**Beam control**
- (DM, TT, PTT, derotation)
- Pola control
- Calibration

**High frequency AO correction**
- (41x41 act.)
- High stability: image / pupil control
- Visible - NIR Refraction correction
  - FoV = 12.5"
  - 40x40 SH-WFS in visible
  - 1.2 KHz, RON < 1e-

**Coronagraphic imaging**
- Dual polarimetry, direct BB + NB.
  - $\lambda = 0.5 - 0.9 \, \mu m$
  - $\lambda/2D @ 0.6 \, \mu m$, FoV = 3.5"

**ZIMPOL**
- 0.95 - 1.35/1.65 $\mu m$
- $\lambda/2D @ 0.95 \, \mu m$
- Spectral resolution: $R = 54 / 33$
  - FoV = 1.77"

**IFS**
- 0.95 - 2.32 $\mu m$;
- $\lambda/2D @ 0.95 \, \mu m$
- Differential imaging: 2 wavelengths,
  - $R \sim 30$, FoV = 12.5"
- Long Slit spectro: $R \sim 50$ & 400
- Differential polarization

**IRDIS**

**Pupil apodisation**
- Focal masks: Lyot, A4Q, ALC.
- IR-TT sensor for fine entering

**Nasmyth platform, static bench,**
- Temperature control, cleanliness control
- Active vibration control
Combined use and advantages of IRDIS/DBI and IFS

Simultaneous use of Y-J band with IFS
Dual imaging in H

- Multiplex advantage for field and spectral range
- Mutual support: false alarm reduction, operation, calibration
- Immediate companion early classification

Astrometric accuracy: 0.5 - 2 mas (depending on SNR)

$10^{-6} (10^{-7})$ at 0.5”

$>1.77” (3’’)$

$5\times 10^{-6} (5\times 10^{-7})$ at 0.9”

$11” \times 12.5”$
- Correct for turbulence
  - Provide a corrected area of 1.5-2 arcsec diameter
  - 60 nm rms on corrected modes => (90% SR in H for typical Paranal conditions)
  - Residual jitter smaller than ±3 (goal 1.5) mas rms
  - Optimal perf for V-mag GS < 9 (goal 10)
  - Good correction (better than NAOS) for GS mag < 12 (goal 15)

- To ensure system stability
  - Optical axis wrt to coronagraphic device < 0.5 mas (goal 0.2)
  - Beam shift on optical surfaces < 0.2% (goal 0.1) of the full pupil diameter
  - Non common path aberrations (down to coronagraph device) < 15 nm rms

- To provide useful data for image post-processing
  - Storage of WFS and control data
  - Estimation of turbulence and system critical parameters
  - Measurement of IRDIS internal defects (differential aberrations)
SPARTA: Standard Platform for Adaptive optics Real Time Applications
SPHERE Deformable Mirror

- CILAS piezo-stack DM delivered end 2007
- Surface quality: 5nm rms
Fast Image Tip-tilt

- "X" bandwidth is 700 Hz at \(-3\text{dB}\) phase shift of \(-15^\circ\) at 80Hz
- "Y" bandwidth is 891 Hz at \(-3\text{dB}\) phase shift of \(-10^\circ\) at 80 Hz
- Goal 1000Hz

Prototype
1.2 kHz, CCD220-based wavefront sensor

- Benefits from the Opticon JRA1 research program (EU funded)
- Common with the VLT AO-facility
  1. pixels, square 24 μm
  2. 100% fill factor and 240x240 square grid array of pixels.
  3. low read noise of < 1 e-/pixel and goal of 0.1 e-/pixel.
  4. range of operating frame rates from 25 frames/s (fps) to 1200fps

- NGC development (ESO)
- Spatially Filtered SH
  - Optimization of the spatial filter size
  - Study of BB impact
  - WCOG: confirmation of the gain in perf (simulation & experimentation)
Main components - RTC

- Based on SPARTA platform
  - Consortium specifications (+ algo)
  - ESO development

- Main features
  - very small global delay (~ 1ms)
  - large number of actuators
  - hybrid control law
    - LQG (Kalman filter based) for TT
    - OMGI for higher modes
  - additional features to deal with SAXO specificities (DTTS, PTTS)

- Status
  - Specifications OK
  - Development:
    - Various version (drops) available for SPHERE during SPARTA development
      => optimization of the AIT period => reduction of risks and planning drifts.
    - First version to be delivered mid-July 2009
Differential Tip-Tilt Sensor
- IR camera located just before the coronagraph mask
- 1 to 10 % of the IR flux for this sensor
- WCoG measurement
- control of a diff. tip tilt plate
- closed loop scheme - 1-10 Hz
- additional capability: focus check between two observations
- Could potentially be used to implement on-line phase diversity (see L Mugnier pres.)

Pupil Tip-Tilt Sensor
- Use of SH data (sub-aperture, intensities)
- PTTM close to the entrance focal plane
- Closed loop scheme
- Frame rate ~ 0.1 Hz
- Residual beam shift < 0.2 % of the full pupil diameter
SPHERE
IRDIS dual beam imager

Young M0 star, 40 pc
1 MJ planet at 0.2"

Old M0 star, 10 pc
10 MJ planet at 0.1"
ZIMPOL performance

GOV, 3 pc
Filter: ZIM R16 (600–900 nm)
Coronagraph: Cl. Lyot, 5 λ/D
Integration: 4 h, 100 screens
Diff.ab.: SCIV
Extraction.: 2x2 gaussian

Noise Curves:
- intensity
- intensity, sign sw
- polarization
- polarization, sign sw
- pol, sign sw, ang avg
- photon limit

Planet Signals:
- intensity
- pol = 0.50
- pol = 0.10
Journées FOST/GRIL

Principe et ordres de grandeurs

Performance en forte évolution

2010's

2020's

~ all stars

R <~ 12

R <~ 9

R <~ ?

5sig DeltaMag contrast

separation (arcsec)

10^8 20

10^6 15

10^2 0.1

10 1

2000's

2000

2010

2010's

2020

~ all stars
Conclusions

- Very challenging project!
- Now at manufacturing stage
- At Paranal in early 2011
- Main science outputs by ~2015 for both:
  - Large surveys for statistical approaches, broad target selection
  - In-depth characterization of specific systems
- Critical step before further exoplanet studies in the ELT era for
  - Technological development
  - System/calibration/operational experience
  - Scientific preparation on the given available target sample
Thank you!
$N_{act} \cdot F_{samp} \Delta \lambda$, the necessary trade-offs

<table>
<thead>
<tr>
<th>GAINS</th>
<th>LOSSES</th>
</tr>
</thead>
</table>
| • $N_{act}$ | • WFS Flux $\propto (N_{act})$  
  ⇒ Loss in limit mag |
| • $F_{samp}$ | • WFS Flux $\propto (F_{samp})^{-1}$  
  ⇒ Loss in limit mag |
| • $\Delta \lambda$ (WFS-im) | • Chromatism effects  
  ⇒  ⇒ contrast |
| ⇒ Corrected area $\propto N_{act}$  
  ⇒ Contrast  
  (profil $\propto (N_{act})^{-8/3}$)  
  ⇒ Contrast $\propto (F_{samp})^2$  
  ⇒ Noise effects $\propto \Delta \lambda^{-2}$  
  WFS spectral bandwidth  
  VIS detector  
  ⇒ Gain in limit mag  
  ⇒ contrast |

⇒ Complex trade-offs: depends on scientific requirements (ultimate contrast, number of targets) and atmospheric conditions
• 41x41 actuators => corrected area +/- 0.82” in H

• “Simplified” Error budget (nm rms) for SAXO

<table>
<thead>
<tr>
<th>Error sources</th>
<th>Low frequencies (nm)</th>
<th>High frequencies (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeing</td>
<td>0.65</td>
<td>0.85</td>
</tr>
<tr>
<td>total for atmospheric limitations</td>
<td>11</td>
<td>14</td>
</tr>
<tr>
<td>total for DM errors</td>
<td>11 (7)</td>
<td>13 (9)</td>
</tr>
<tr>
<td>Total for temporal errors</td>
<td>19 (15)</td>
<td>23 (18)</td>
</tr>
<tr>
<td>Total for residual aliasing error</td>
<td>20 (13)</td>
<td>32 (23)</td>
</tr>
<tr>
<td>Total for noise related errors</td>
<td>42 (35)</td>
<td>44 (36)</td>
</tr>
<tr>
<td>Total for mis-calibration errors</td>
<td>10 (5)</td>
<td>10 (5)</td>
</tr>
<tr>
<td>TOTAL for the AO main AO loop</td>
<td>54 (43)</td>
<td>62 (49)</td>
</tr>
</tbody>
</table>

• Telescope/instrument defects
  • in the corrected area: static / quasi-static => fully corrected by AO
  • high freq : no correction - included in the global system error budget

41x41 actuators
1.2 KHz
Filtered SH-WFS
EMCCD, WCoG, BB WFS
NCPA comp.

TOTAL for the AO main AO loop 52.8 64.0